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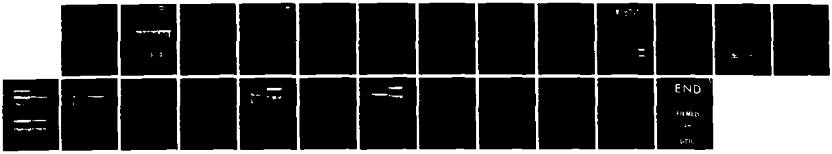

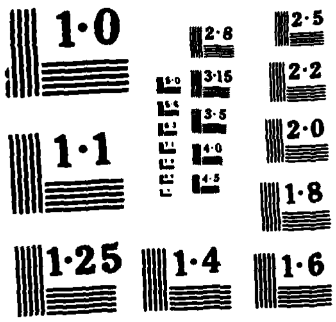

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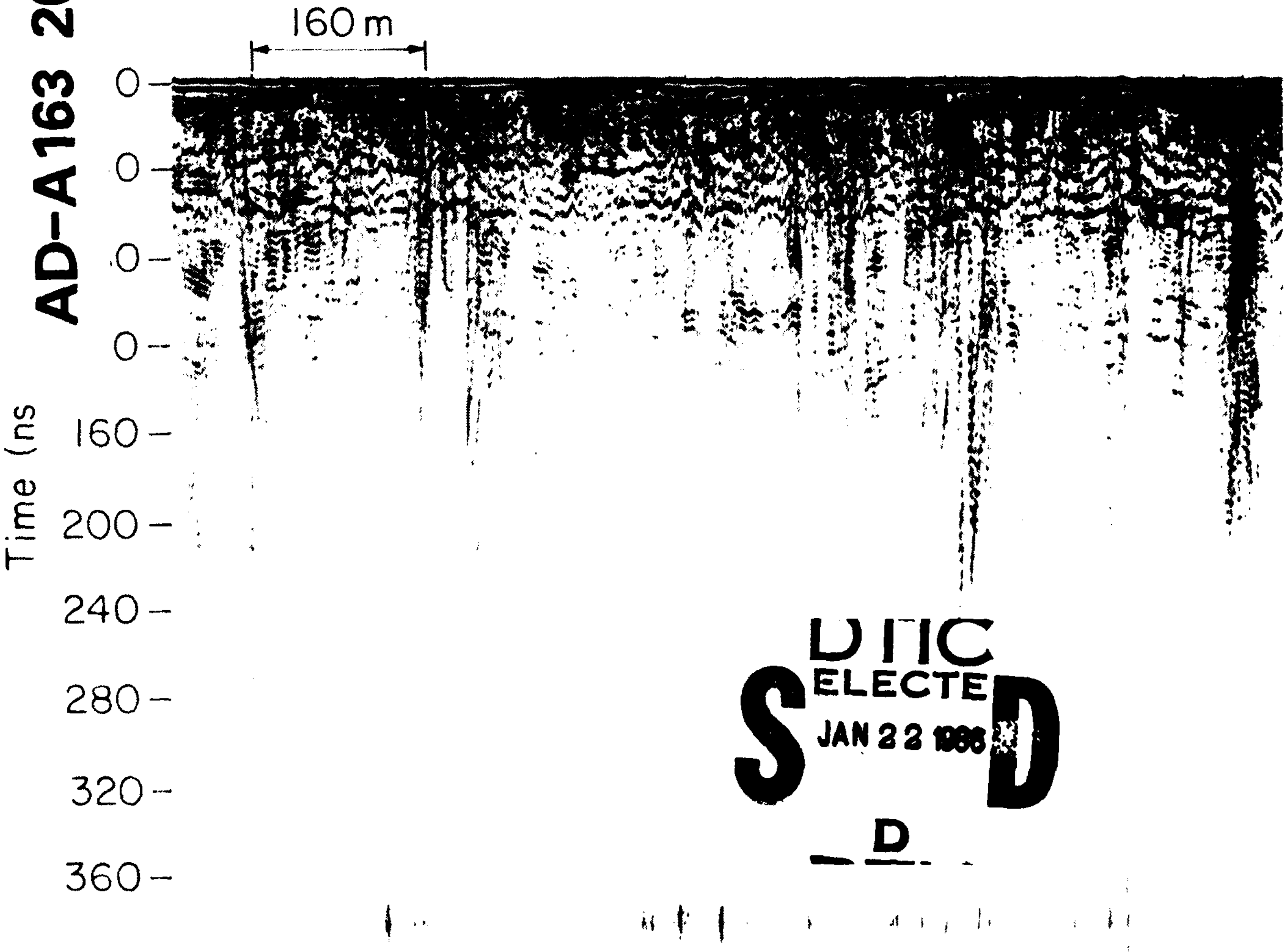
Model studies of surface noise interference in ground-probing radar



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Near-surface silt-filled ice wedge casts interfere with a deep, linear feature (water table at 200 ns) in a radar record.

CRREL Report 85-19

November 1985

Model studies of surface noise interference in ground-probing radar

Steven A. Arcone and Allan J. Delaney

Prepared for
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Ground-probing radar can be an effective tool for exploring the top 10 to 20 m of ground, especially in cold regions where the freezing of water decreases signal absorption. However, the large electrical variability of the surface, combined with the short wavelengths used, can often cause severe ground clutter that can mask a desired, deeper return. In this study a model facility was constructed consisting of a metallic reflector covered by sand. Troughs of saturated sand were emplaced at the surface to vary surface electrical properties and to act as a noise source to interfere with the bottom reflections. Antenna polarization and height, and signal stacking in both static (antennas stationary) and dynamic (antennas moving) modes were then investigated as methods for reducing the surface clutter. Polarization parallel to the profile direction (perpendicular to the troughs' axes) gave profiles superior to the perpendicular case because

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of the directional sensitivity of the antenna radiation. Dynamic stacking greatly improved the signal-to-noise ratio because noise sources were averaged as the antennas moved, while the desired reflector, buried at constant depth, was enhanced. Raising the antennas above the surface also reduced noise because the surface area over which reflections were integrated increased. All three noise reduction techniques could be effective in surveys for reflectors at nearly constant depth such as groundwater tables or ice/water interfaces if the lateral variation in undesired ground properties is sufficiently random.

PREFACE

This report was prepared by Dr. Steven A. Arcone, Geophysicist, and Allan J. Delaney, Physical Science Technician, both of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A762730AT42, *Design, Construction and Operations Technology for Cold Regions;* Task D, *Cold Regions Base Support: Design and Construction;* Work Unit 011, *Electromagnetic Geophysical Methods for Rapid Subsurface Exploration.* This report was technically reviewed by Dr. Kenneth Jezek and Dr. Lindamae Peck of CRREL.

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MODEL STUDIES OF SURFACE NOISE INTERFERENCE IN GROUND-PROBING RADAR

Steven A. Arcone and Allan J. Delaney

INTRODUCTION

Geophysicists explore surface geology using mainly electrical or electromagnetic techniques. These methods are often able to discriminate changes in electrical properties on the order of metres, depending on parameters such as frequency, antenna size, probe separation, etc. Such detail is often required, for example, when surveying ice thickness, groundwater tables, permafrost tables, or depth to bedrock, or when mapping buried utilities, ordnance or wastes. Of the several electromagnetic methods available, subsurface radar offers the best possibility for acquiring the most detail. Articles by Bertram et al. (1972), Morey (1974), Annan and Davis (1976), Kovacs and Morey (1979), Arcone and Delaney (1982, 1984), Arcone et al. (1982), and Sellmann et al. (1983) have all shown radar's ability in a variety of geologic environments. In this paper we utilize experimental modeling to examine some techniques for decreasing the contributions from unwanted surface disturbances to a simple radar record.

Subsurface radar profiling experiences the same types of incoherent and coherent noise problems as do seismic or radio echo sounding techniques. Incoherent noise may be generated within the radar system or externally as from lightning discharges or solar activity. This type of noise is random and can be greatly reduced by stacking (adding consecutive returns) at each antenna position so that the noise will not add as strongly as will the signals. Coherent noise or clutter generally means unwanted reflections that mask or interfere with the desired reflection. The main types of coherent noise result from scattering and diffraction from electrical boundaries that may change abruptly in direction or whose radii of curvature are comparable to the wavelengths transmitted. Resonances such as multiple reflections between layers or between the antennas and the ground are also considered coherent noise. Techniques such as common depth point stacking, deconvolution and migration (e.g., Telford et al. 1976) have helped to eliminate these problems in seismic exploration but their use has yet to be reported on for subsurface radar.

The most common sources of coherent noise are the large-scale variations in electrical properties that occur within about the first metre of ground, usually because of changes in water content. Diffraction and multiple reflections originating in this zone can cause disturbances far into a radar record (Fig. 1). Radar antennas for subsurface profiling are broadband devices and are generally designed to deliver maximum power over their bandwidth to a homogeneous, nonconducting dielectric whose relative permittivity is about 4. Consequently, when the electrical properties vary, so will the power transmitted into the ground and the frequency spectrum of the signal. In addition, a rough ground surface may repeatedly lift the antenna causing clutter because of decoupling from the ground.

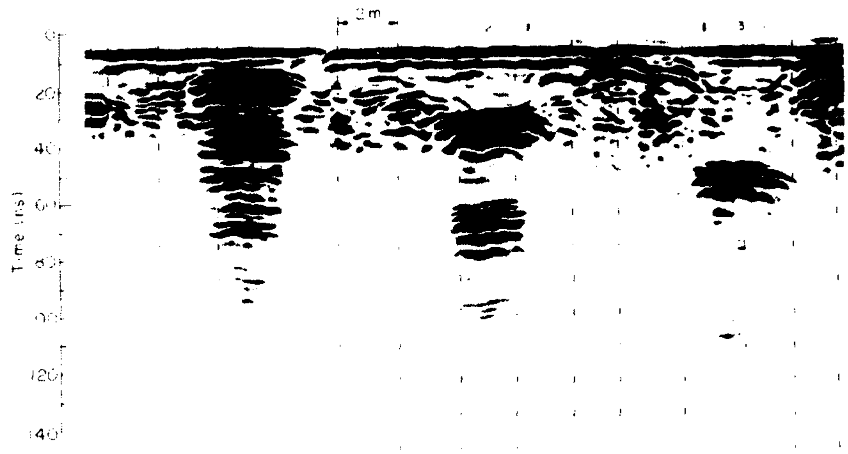


Figure 1. Example of coherent, near-surface noise. One-, two- and three-meter-deep artificial reflectors are causing multiple reflections for over 100 ns.

OBJECTIVE AND PROCEDURES

The objective of this study was to determine the effects of antenna polarization, height above the surface and stacking upon the reduction of coherent noise from a surface layer of periodically varying dielectric properties. The coherent noise interfered with the desired return from a strong reflector placed at a uniform depth of about 70 cm below an unsaturated sand overburden, all of which were contained in a large wooden enclosure that was approximately 4.9×2.4 m.

A broadband, subsurface profiling radar antenna with a dominant wavelength of about 40 cm was used to traverse the sand surface. We varied the surface layer dielectric properties by emplacing several parallel troughs that were filled with water-saturated sand and enclosed in polyethylene. Antenna height was varied by placing polystyrene slabs over the sand surface. The returns were stacked automatically by the radar control unit while the antennas were towed at uniform speed.

MATERIALS AND METHODS

Subsurface radar

Subsurface or ground-probing radar has been commercially available since the early 1970's. Its principles of operation have been described extensively in many of the references cited above and will only be briefly reviewed. Most of the emphasis here will be on the antenna.

In subsurface radar, separate transmit and receive antennas are employed because echoes may be received within nanoseconds of transmitting. The basic signal radiated from the transmit antenna is a short sinusoidal signal as shown in Figure 2. The spectrum of this pulse is usually centered in the VHF or UHF range. The lower frequencies are used for deeper penetration. The pulse repetition rate is about 50 kHz or 1 pulse every 20,000 ns. The returns from several thousand pulses are sampled and compiled to produce one audio frequency facsimile of the echoes (called a scan) so that it may be recorded on magnetic tape. The sampling rate is dependent on the scan time range selected (50–2000 ns). The time used for producing the facsimile scan may range from 125 ms (8

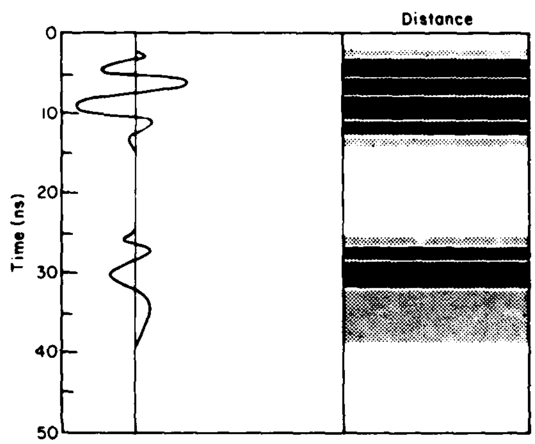


Figure 2. Idealized pulse returns and equivalent Z-type graphic display should these returns remain unchanged with distance.

scans/s) to 20 ms (50 scans/s) depending on the manufacturer.

The compiled scans may be displayed as single waveforms or composited into the Z-type graphic display shown in Figure 2. The Z-type display is generally used for analog recordings. Here the horizontal axis is calibrated to antenna position (distance) and the vertical axis is time in nanoseconds. The intensity (darkness) is proportional to signal amplitude so that thin white lines indicate zero crossings of the signal.

Scan waveforms are displayed when returns are recorded in the digital mode. In this mode signal processing is now possible and the primary process is stacking. Our system may sum 16, 32 or 64 consecutive scans to enhance the signal-to-noise ratio. Generally, this is done with the antennas stationary, which reduces random noise. In this study we also stacked 64 scans with the antennas moving. Our intention was to randomize the surface reflections by moving the antennas, while still reinforcing the desired echo from the subsurface reflector at uniform depth.

The antennas used were resistively loaded "bat wing" (biconical projections) type dipoles (Fig. 3). The resistive loading limits current resonance and, along with the bat wing shape, gives the antenna its broadband characteristics. The antenna pulse emitted into air is shown in Figure 4 along with the pulse spectrum. The physical shortness of the pulse allowed us to do modeling in a relatively shallow basin (0.7-m depth). Spatially, the far field beam does not form until a distance $2D^2f/c$, where D is the effective length of the antenna, f is frequency and c is the free space propagation velocity 30 cm/ns. This formula gives a far field distance for our antenna of only 12 cm at the center of the band ($\approx$ 800 MHz). The radiation pattern of an interfacial dipole is multi-lobed (Engheta et al. 1982) and the 3-dB width as defined by the outer lobes is estimated at about 100° from broadside.

In any profile for which the antennas are towed at fixed spacing, the first signals received will be the direct coupling through air and then through the ground. The duration of this direct coupling is the time during which no subsurface echoes can be distinguished. After this first "event," the echo time of return t is found from the formula

$$t = (2d\sqrt{k})/c$$

where d is the depth and k is the dielectric constant. The pulse will retain its shape for all time if it propagates in a nondispersive (k is independent of frequency) or nonscattering medium.

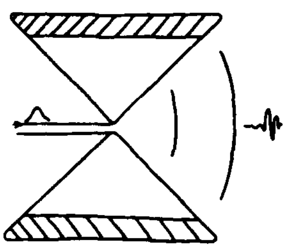


Figure 3. Broadband dipole that transforms the Gaussian pulse at left to the wavelet at right. Shaded portions represent resistive coating to dampen current oscillations.

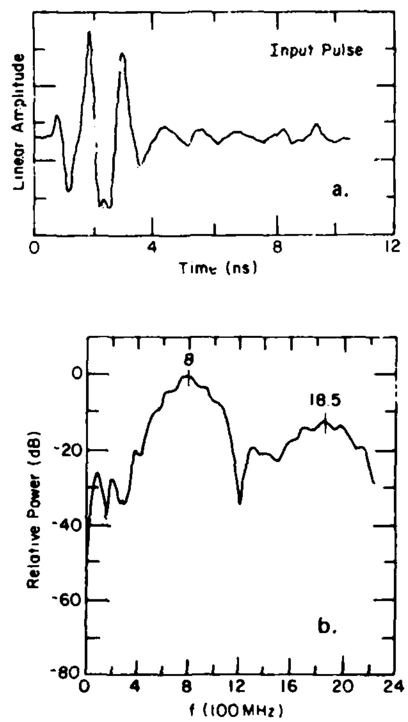


Figure 4. Transmitted pulse (a) in air of the GSSI 101C antenna and its associated power spectrum (b).

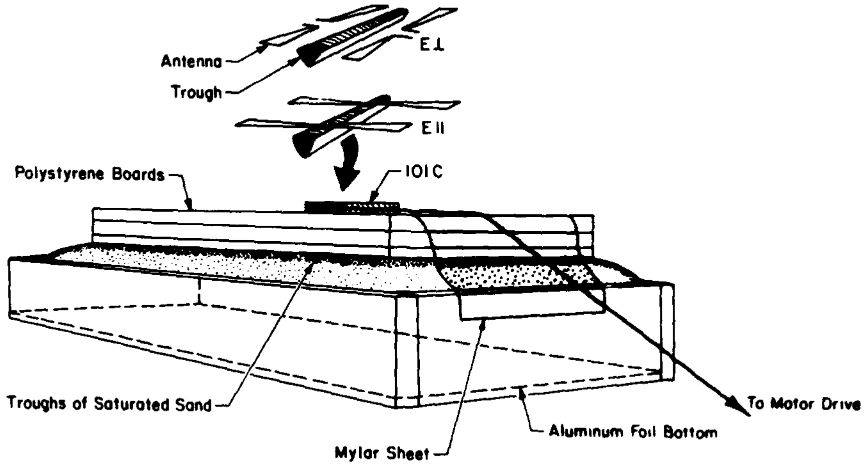


Figure 5. Schematic of the test facility. E⊥ *and* E∥ *indicate antenna electric field polarization perpendicular and parallel, respectively, to the profile direction.*

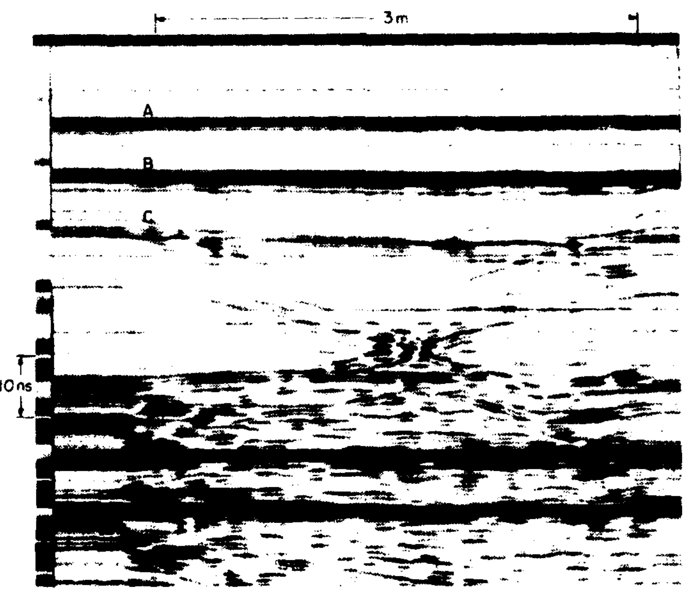


Figure 6. Radar profile of the sand fill (parallel polarization). A is the direct coupling, B the primary bottom reflection and C its multiple.

Model facility

The model facility is depicted in Figure 5. Aluminum foil was placed at the bottom of the box, which was then filled with sorted, washed sand ($\approx$ 0.8 g H_2O/cm^3) to a height of about 70 cm. The value of k for the sand was about 4 giving $t = 9.3$ ns, which was sufficient to separate the direct coupling, primary and multiple bottom reflections from each other. The sides of the sand were intentionally sloped at about a 45° angle to reduce the possibility of side wall reflections interfering with the primary bottom reflection. A thin sheet of mylar was placed on the sand to allow the antennas to be pulled smoothly with a motor drive. A radar profile of the undisturbed sand is shown in Figure 6 and reveals that the primary reflection did not experience interference from any other reflections.

We made radar profiles at a constant height above the sand surface by placing polystyrene boards on top of the sand (Fig. 5). Polystyrene has a $k < 1.1$ and so provided no significant waveguiding or sidewall reflection. Surface disturbances were created by emplacing troughs of saturated sand encased in polyethylene at the sand surface. The troughs were about 5 cm^2 in cross section, flush with the surface, and spaced 30 cm apart as shown in Figure 5. Also shown in the figure are the antenna polarization and its nomenclature.

RESULTS

The results presented are analog recorded graphic profiles and digitally recorded waveform profiles of the model facility. For each profile we indicate polarization used, the height of the antenna in centimetres above the surface, and relative overall gain setting in decibels for the digital profiles. Greater gain was applied when the antennas were elevated in an effort to keep all bottom return signal levels equal. All the digital profiles were recorded using a Xadar Electromagnetic Reflection Profiling System on the scan range of 50 ns as marked on the unit. The actual calibrated time scale is 4.3 ns per division for the waveform recordings using an exponential Time Range Gain (TRG) function that was applied for the first 21.5 ns. All analog recordings, except the two presented at 40 cm height, were made with a GSSI Subsurface Interface Radar which employs an exponential TRG function throughout the entire scan. The analog profiles at 40 cm were made with the Xadar system because by then we had acquired the proper equipment to mate the GSSI antenna with the Xadar control unit.

Isolated disturbances—surface and raised analog profiles

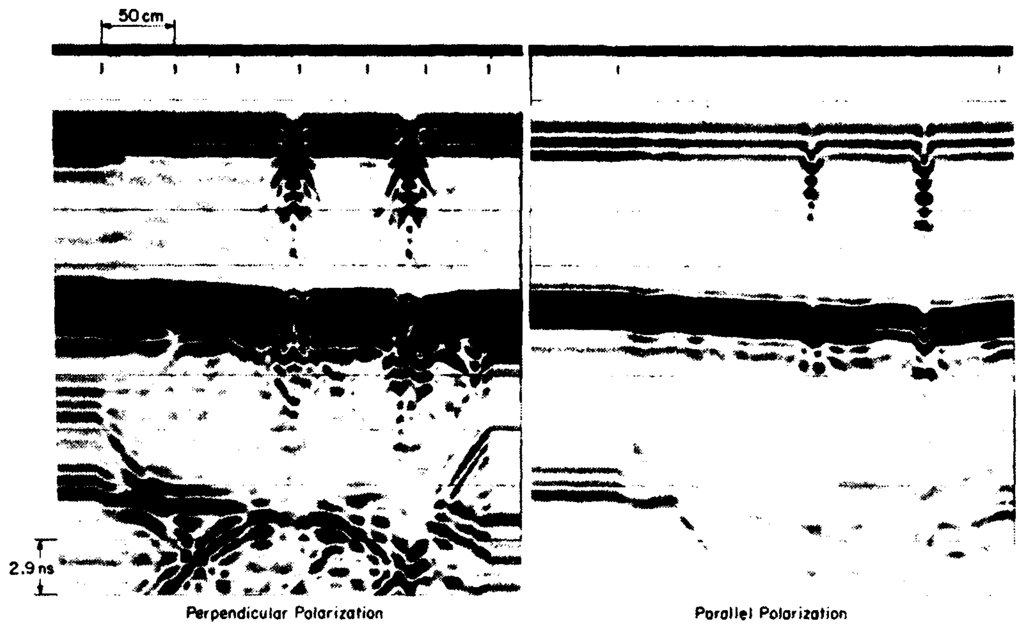
Figure 7 shows analog profiles over two isolated saturated-sand troughs. Figure 7a is for the antennas lying on the sand surface and Figure 7b is for when they were elevated 40 cm above the surface. The profile on the left of each figure is for perpendicular polarization and on the right is for parallel. In both cases of Figure 7a the directly coupled waves between the antennas are slowed by the saturated sand in the troughs as revealed by the dip in the topmost band, which is the direct coupling. The perpendicular polarization responds much more strongly to the trough response because the polarization is parallel with its long axis, thus displaying the greater sensitivity of a dipole in its broadside direction. The response is hyperbolic and reverberatory near the trough, and it disturbs the bottom reflection from the aluminum sheet by distorting the transmitted waveform. The parallel case shows far less disturbance to the bottom reflection because of the relative insensitivity of the antenna in its endfire direction (direction along the antenna axis).

The profiles at elevation in Figure 7b are extremely similar to each other and differ mainly in the gain that was applied. Thus, all returns for the perpendicular case are more intense than those for the parallel. The hyperbolic trough responses are broader than in Figure 7a, but since the troughs are in the far field of the antennas (and consequently do not change the transmitted power) and are narrow in comparison with the center frequency wavelength ($\approx$ 38 cm) (and so scatter less effectively), they offer little disturbance to the bottom reflection.

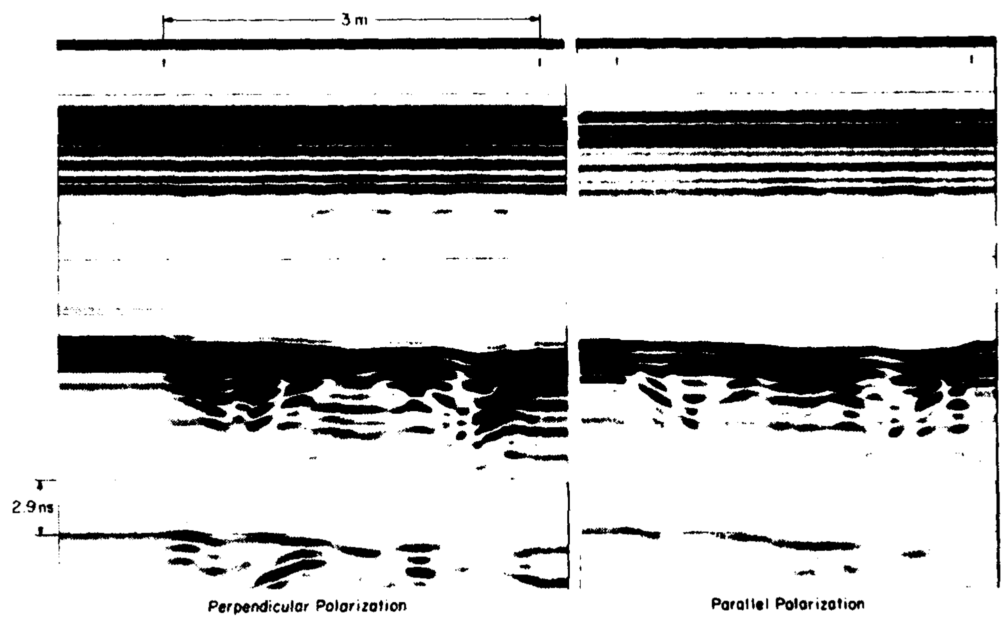
Multiple disturbances

Surface analog and digital profiles

Figures 8 and 9 show surface traverses over multiple troughs in both the analog and digital modes. Figure 8a compares the analog perpendicular and parallel profiles, which suggest the same conclusions that were drawn for Figure 7a. The perpendicular case shows that the antennas were much more sensitive to the troughs, and it produced the greater disturbance to the desired bottom reflection. This bottom reflection is periodically suppressed twice as often as the troughs appear since each antenna had to pass separately over each

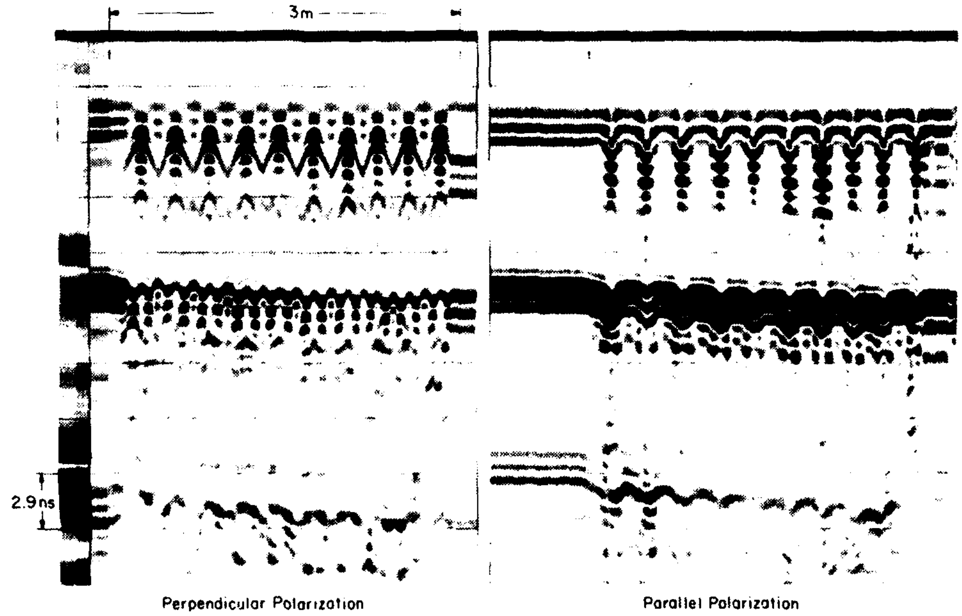


a. Antenna lying on surface.

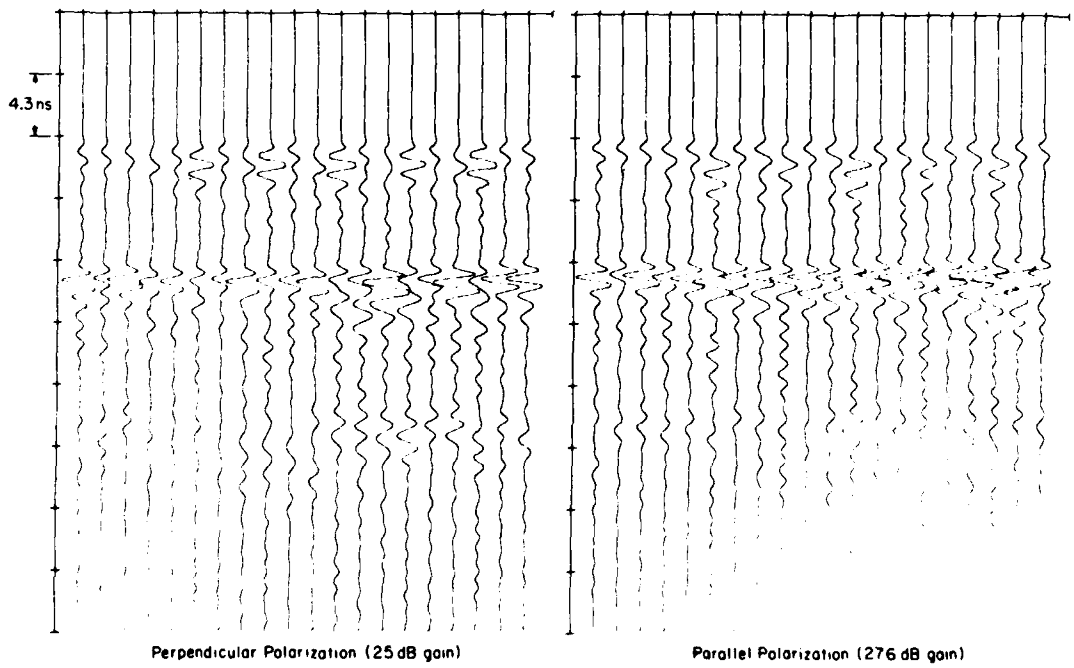


b. Antenna raised 40 cm above sand surface.

Figure 7. Analog traverse over two saturated sand wedges.



a. Analog mode.



b. Static 64 stack mode.

Figure 8. Perpendicular and parallel polarization surface traverses over multiple troughs.

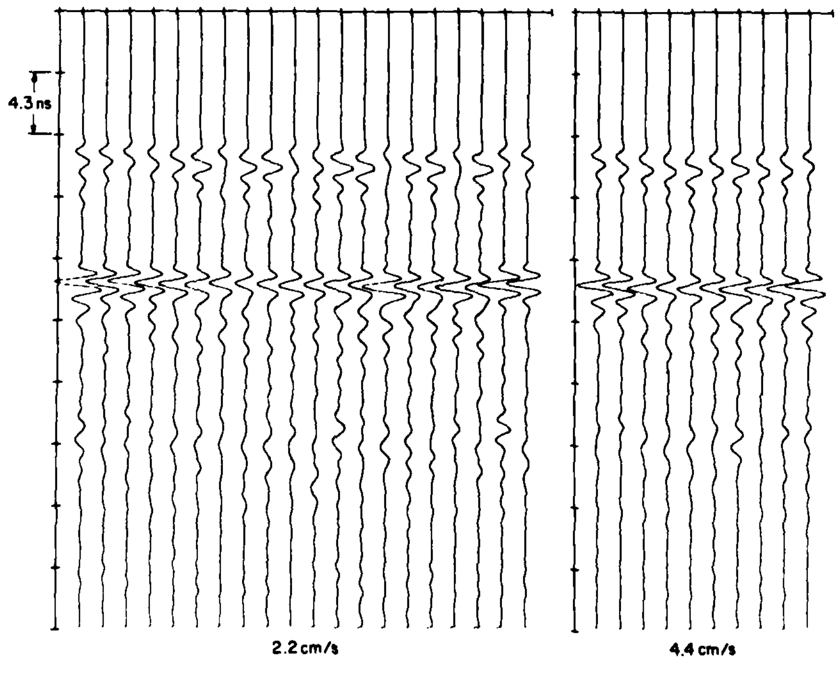
trough. The parallel case reveals that the antennas were sensitive to the troughs only when they were close to them, and the bottom reflection shows superior continuity. In this case both antennas pass over the troughs simultaneously, thus disturbing the bottom reflector only once for each trough.

Figure 8b makes the same comparison in the digital mode. Each profile is composed of 20 echo scans, each of which is the result of stacking 64 individual scans while the antennas were stationary. Consequently, only random, incoherent noise is reduced. The antennas were uniformly spaced, but each did not fall exactly on a trough or in between two troughs, i.e., the frequency of the antenna position is out of phase with that of the troughs so that sometimes the antennas were directly over the troughs, sometimes partially over, etc. As with Figure 8a the parallel case shows far less disturbance to the bottom reflector than does the perpendicular. All the bottom reflection wavelets are very similar in the parallel case, whereas in the perpendicular case many of the wavelets are distorted.

Figure 9 has an added dimension that improves both the perpendicular and parallel profiles. In these profiles, the returns were stacked while the antennas were being towed at uniform speeds of 2.2 cm/s (left profile) and 4.4 cm/s (right profile). Consequently, as the antennas moved, the only signals that were consistently coherent were the bottom reflections. The higher speed produced the cleaner record because a greater number of unwanted and comparatively incoherent returns were averaged in the stacking. These results are similar to those sought in the seismic technique of Common Depth Point (CDP) stacking except that here, the desired reflector must remain at uniform depth. In the CDP technique, signals are gathered from single reflection points along a vertical line. Here they are gathered from single reflection points along a horizontal line.

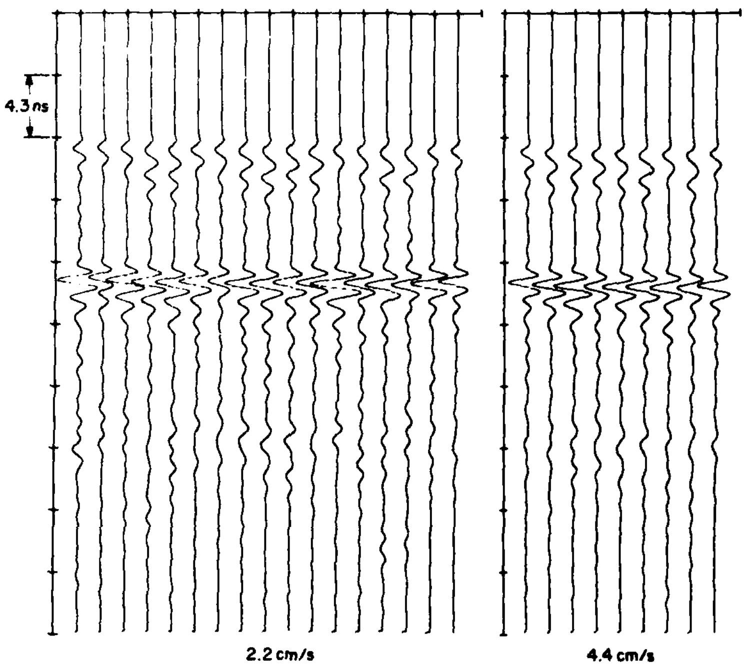
Analog and digital profiles as a function of height

The surface profiles were repeated at heights of 10, 20, 30 and 40 cm above the sand. All of these profiles demonstrated that quality is maintained at height, but no one particular height showed any exceptional improvement over the dynamically stacked surface profiles. Therefore, only the pro-



a. Polarization perpendicular to the profile direction.

Figure 9. Surface traverses over multiple troughs in the dynamic 64 stack mode at two different towing speeds (2.5 dB gain).



b. Polarization parallel to the profile direction.

Figure 9 (cont'd).

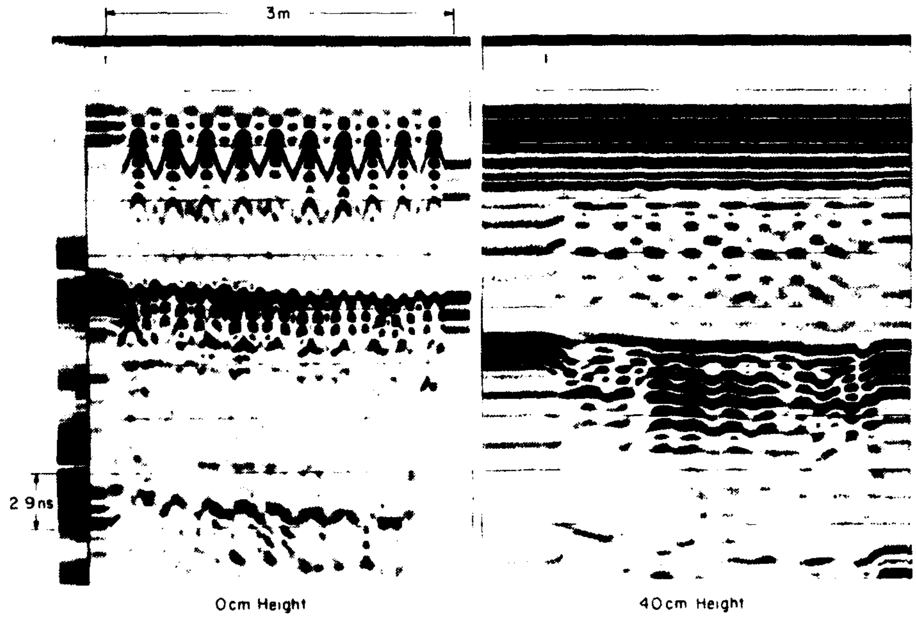
files at 40 cm are presented for qualitative comparison. Figure 10 presents the results for perpendicular polarization and Figure 11 presents those for parallel. Approximately 10 dB of gain was applied to the 40-cm profiles to make the peak amplitudes of the bottom reflection about equal to those at the surface. All signals other than the direct coupling and the bottom reflection are considered noise.

Figure 10a compares the perpendicularly polarized analog profiles at the surface and the 40-cm height. The prominent hyperbolas at the top of the surface profile degenerate into a vague criss-cross pattern in the center section of the 40-cm profile. The new set of heavy bands at the top of the 40-cm profile are the direct coupling between the antennas, followed by the surface reflection which occurs at about a 2.7-ns delay. The desired bottom reflection is still apparent but is irregular in comparison with that for the parallel polarization case (Fig. 11a) discussed below.

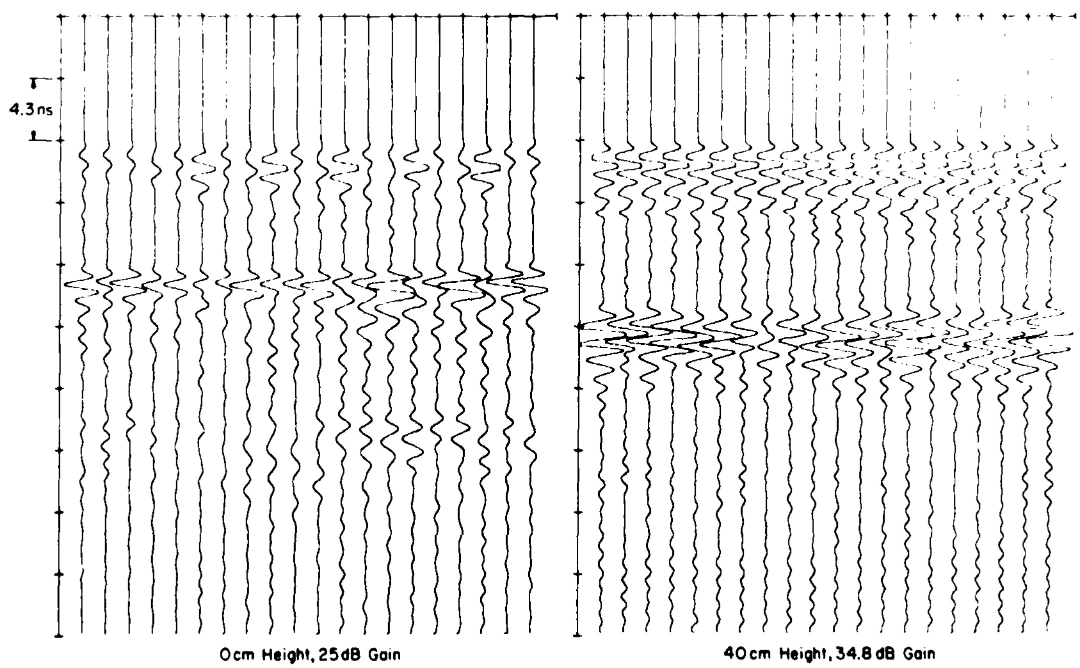
Figure 10b compares the statically stacked profiles. The 40-cm profile shows the better signal-(peak amplitude of the bottom reflection)-to-noise ratio during the time intervals immediately before and then after the bottom reflection. For the noise before the bottom reflection, the improvement is estimated at about 2.5 dB while after it is about 10 dB. In addition, a greater consistency in waveform can be seen in the 40-cm profile.

Figures 10c and 10d reveal similar comparisons considering the higher peak signal levels that occur in the 40-cm profiles. During the 4-ns interval preceding the bottom reflection in both Figures 10c and 10d, ripples of about the same amplitude occur, yet the 40-cm signal level of the bottom reflection is generally 30% higher than that of the surface profile, thus giving an improvement of about 2 dB in peak-signal-to-peak-noise ratio. During the time interval following these reflections in both figures, the larger-scale noise fluctuations at the surface have been reduced by about 60% at 40 cm, considering the greater signal level at 40 cm. A comparison of the signal-to-noise ratios between the statically (Fig. 10b) and dynamically stacked profiles at 40 cm revealed no difference when only peak amplitudes were considered, either before or after the bottom reflection. However, it is apparent that the rms level of noise at the surface is reduced by dynamic stacking.

Figure 11a presents the parallel polarized analog profiles at both the surface and 40-cm height. Both profiles show a bottom reflection superior to the perpendicular polarization cases of Figure 10a.

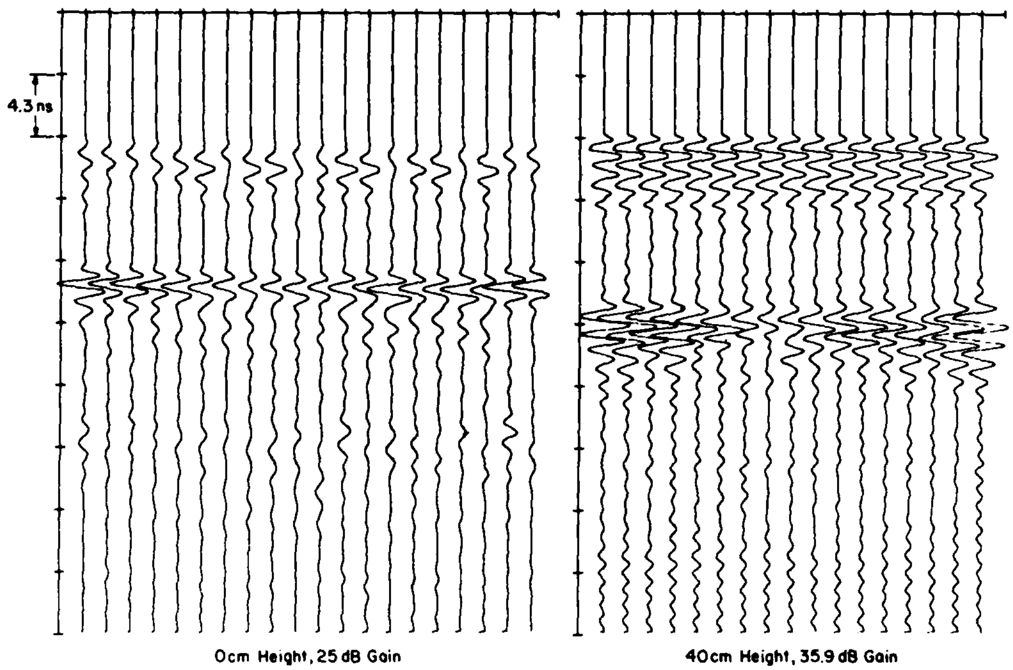


a. Analog profiles.

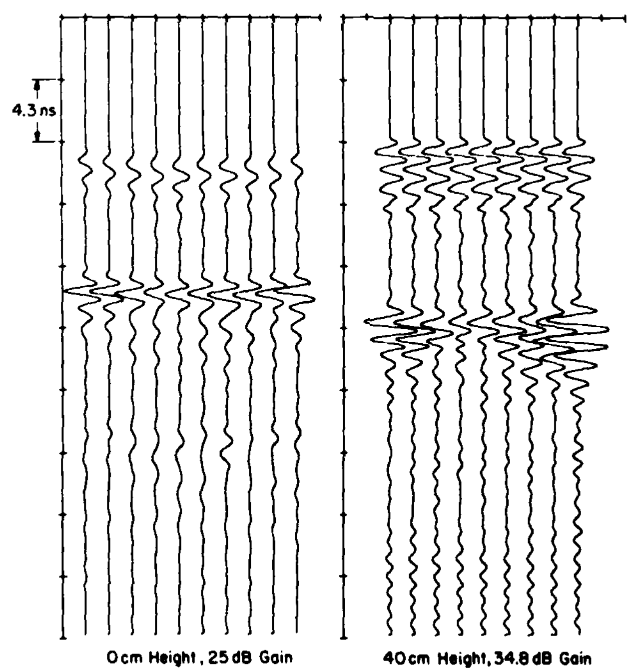


b. Static stacking.

Figure 10. Comparison of profiles with perpendicular polarization at the surface and 40-cm height.

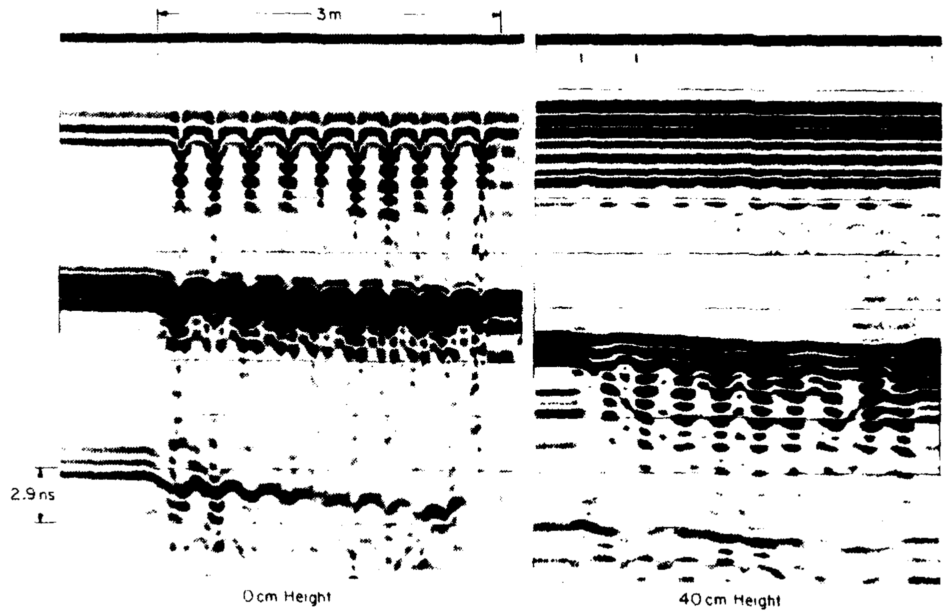


c. Dynamic stacking at 2.2 cm/s.

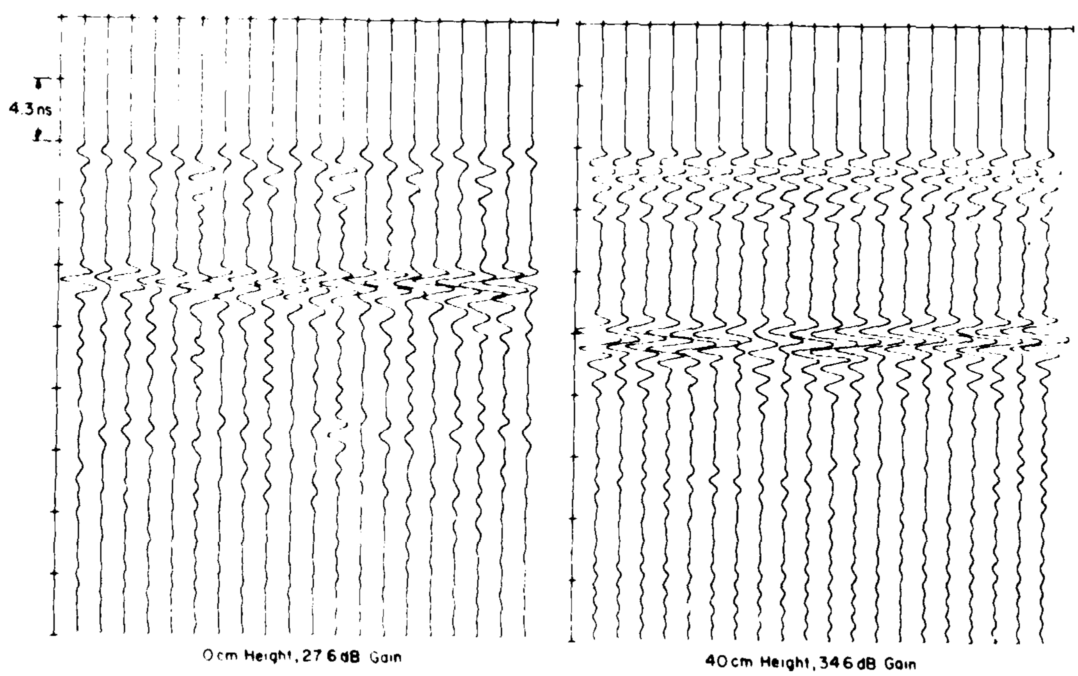


d. Dynamic stacking at 4.4 cm/s.

Figure 10 (cont'd).

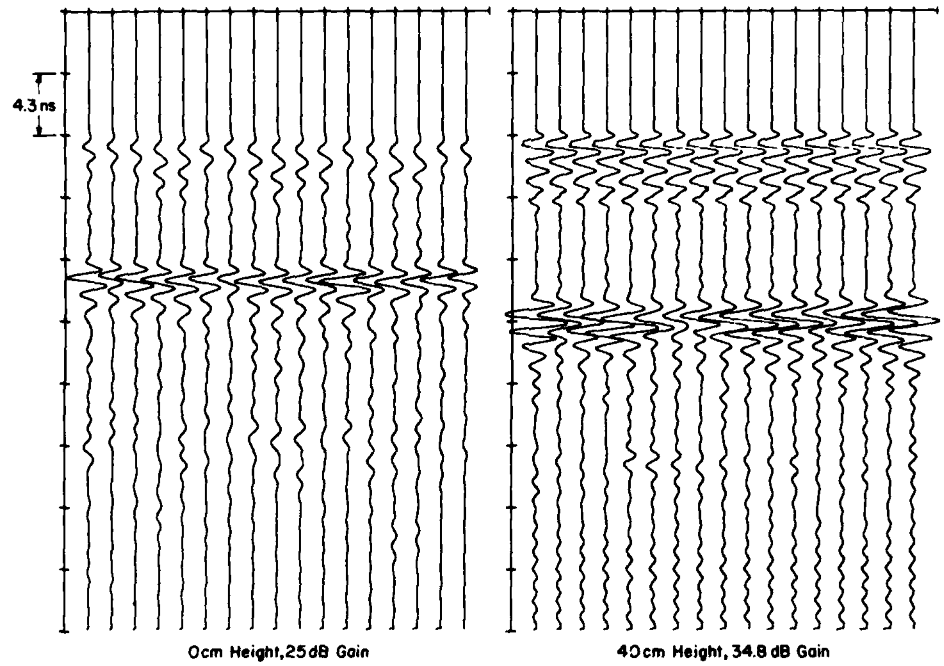


a. Analog profiles.

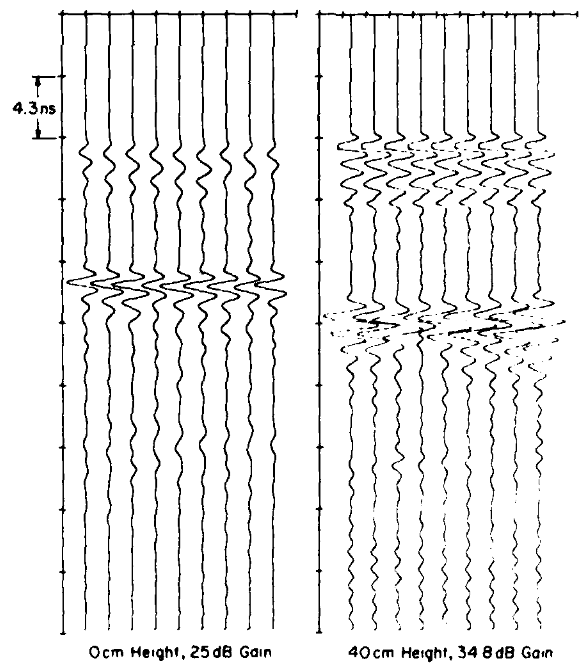


b. Static stacking.

Figure 11. Comparsion of profiles with parallel polarization at the surface and 40-cm height.



c. Dynamic stacking at 2.2 cm/s.



d. Dynamic stacking at 4.4. cm/s.

Figure 11 (cont'd).

The effects of the saturated troughs on the 40-cm profile can be seen by the nine horizontally aligned disturbances occurring below the main return of the bottom reflection. This contrasts with the 40-cm profile of Figure 10a which shows trough interference throughout the bottom reflection.

Figure 11b compares the statically stacked profiles using parallel polarization. Again, the increased gain level at 40 cm makes the peak signal amplitude of the bottom reflection nearly equal to that in the surface profile. However, the peak noise level at 40 cm is only half of what it is at the surface.

Figures 11c and 11d present the dynamically stacked profiles. In contrast with the perpendicular case at 40 cm, there is an increase in signal-(bottom reflection)-to-noise ratio ($\approx$ 6 dB) over that of the statically stacked profile for the noise in the 4 ns preceding the bottom reflection. After the bottom reflection occurs, the peak noise level relative to the peak signal level is about the same ($\approx$ 14 dB) in both the static and dynamic stacking cases.

DISCUSSION AND CONCLUSIONS

The objective of this study was to determine the effect of polarization, height and stacking upon reducing coherent noise from a surface layer whose electrical properties varied within distances on the order of a wavelength of the dominant frequencies of the radar pulses. The results can be extended to a variable layer at any depth between the antenna and the target reflector because the intervening polystyrene may be considered an earth material with a dielectric constant of unity.

From these studies we can conclude the following:

1. Polarization can reduce coherent noise if the unwanted electrical disturbances are predominantly aligned in a particular direction. When the antennas are nearly in contact with the disturbance, the noise can reverberate deep into the record. If the antennas are at a distance, the noise reduction will depend on the sensitivity of the antennas' transmitting and receiving radiation patterns in the direction of the disturbance. Disturbance directions more nearly aligned normal to the antenna axis will give the greatest sensitivity. This was also demonstrated in a field study by Jezek et al. (1979) who mapped bottom crevasses on the Ross Ice Shelf using radar.

An additional effect not encountered here is the waveguide filter effect. If the disturbances had been spaced closer than an in situ half wavelength, transmission through the layer would have been virtually impossible for the perpendicular polarization case. This is the cutoff effect commonly known in the theory of waveguides (see, e.g., Ramo et al. 1965). The spacing of the troughs would had to have been less than 10 cm for this to have happened.

2. Stacking greatly eliminates coherent noise when done while the antennas are moving, provided that the direct antenna coupling does not vary. It will not eliminate a desired echo so long as the reflector of interest remains at constant depth. If the reflector does slope in the direction of traverse, the total change in depth along the distance that the antenna travels while doing one stack should not exceed about $^1/_{16}$ of an in situ wavelength. In our case, we used a 64 stack, which takes about 8 seconds to compile and during which the antenna moved either 17.6 or 35.2 cm. A $^1/_{16}$ of an in situ wavelength was about 1.2 cm. Consequently, we would still have obtained our desired bottom reflection if the aluminum bottom reflector had been sloped as much as 4° ($\tan^{-1}$ 1.2/17.6) for the low speed or 2° ($\tan^{-1}$ 1.2/35.2) for the higher speed.

3. Height also reduced coherent noise, as was found in the parallel polarization case. This results from a greater area of sensitivity being encompassed by the radiation pattern, thus allowing a greater integration of energy within each return. It is possible that particular heights of polarization orientations may exist where the backscatter from inhomogeneities will add in phase. However, this should not be of such a significant amplitude so as to obscure the bottom reflector.

The results of these experiments should apply to any ground-based or airborne radar exploration program where the objective is the identification of an extensive planar feature. Such features might be groundwater tables, freezing fronts, permafrost tables or the bottom of an ice or snowpack, while the interfering noise could originate from rocks, ice masses, puddles, vegetation, etc. For airborne work, the maximum acceptable geologic slope relative to the surface will be greatly reduced because of the increased speed of the antennas. This reduction can be compensated for slightly by using lower frequency (longer wavelength) antennas. For example, at a speed of 28 m/s ($\approx$ 100 km/h) at an in situ wavelength of 3 m (center frequency of 50 MHz and $k = 4$), an eight stack taking 1 second to compile would allow a maximum slope in the profiling direction of only 0.4°. A 10-MHz center frequency with a four stack would increase this to 4°.

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